EXECUTIVE SUMMARY

Science Overview

The United States Naval Observatory (USNO), the jet Propulsion Laboratory (JPL), and the Naval Research Laboratory (NRL), have joined forces to develop this proposal for the Fizeau Astrometric Mapping Explorer (FAME). This flight investigation will measure, to an accuracy of 10% or better, the absolute distances and proper motions of a complete sample of stars brighter than 14^{th} magnitude that lie within 2.5 kiloparsecs of the Sun. We will use these data to definitively address a set of key scientific objectives that have far-reaching significance for astrophysics and cosmology. These objectives include fundamental calibration of the absolute luminosities of a significant number of Galactic Cepheid and RR Lyrae stars, which will serve to calibrate with unprecedented accuracy the cosmological distance scale for nearby galaxies and clusters of galaxies.

The survey will include significant numbers of all known classes of stars, as well as binaries and multiple systems, clusters and star-forming complexes. The accurate determination of distances, proper motions, colors and magnitudes will enable fundamental advances to be made in a diversity of longstanding problems of galactic and stellar astronomy and astrophysics. Key design and performance characteristics of the FAME mission are summarized in Table ES- 1.

Department of Defense Interest

The proposed investigation will produce an archival catalog of positions and proper motions that will meet the operational need of the United States Department of Defense in the next century. The catalog will achieve an absolute astrometric accuracy of better than 50 μas for stars of 9th magnitude and brighter.

The FAME Team

Our fifteen-member science team represents ten US and European academic and government institutions. The team has broad experience with ground based astrometry techniques and space flight programs (including Hipparcos), and is well qualified to guide the development of FAME. The engineering team is similarly experienced with precision ground and space-based optical systems (including the Hubble Space Telescope), and low cost spacecraft development (Clementine).

Cost

FAME represents a unique opportunity for collaboration between NASA and the Department of Defense. In addition to an intellectual partnership, we propose a cost-sharing relationship where the DoD will assume full responsibility for providing the FAME spacecraft. The cost to NASA for the instrument payload, mission operations, and science, through launch plus 30 days is only $43M in FY94 dollars. The Mission Operations and Data Analysis cost to NASA is $9.9M in FY94 dollars.

Table. ES-1 FAME Mission Summary.

<u>Mission Performance</u>	
Number stars	10 million
Limiting magnitude	V= 15
Astrometric accuracy	<50 μas ($V \leq 9$)
	<1.0 mas ($V \leq 16$)
Systematic	<20 μas
Radiometric accuracy	0.05 ($V \leq 9$)
<u>Instrument Payload</u>	
Beamsplitter	Glass
Telescope	
Design	Reflective
Focal length	36m
Aperture	0.6x0.2m
Field of view	
Size	Two 0.5x0.1deg

Angle between fields	89deg
Detectors	
Type	CCD, backside-illuminated
Pixel size	15x30µm
Format	4096x1024
Number	10 science, 2 rotation-rate
Operating temperature	-70°C
Spectral bands	eight, 0.5 to 0.9 µm
Mass	105kg
Power	200W

<u>System</u>

Mission duration	2.5 yrs
Science orbit	
Perigee	30,000km
Apogee	200,000km
Attitude control	Cold gas
Rotation rate	144 arcsec/sec
Angle between s/c and sun	45 deg
Precession of rotation axis	6 deg/day
Data rate	50 kbits/sec
Power from fixed solar panels	350 W
Mass	
Launch	418 kg
Science orbit	317 kg

1.0 SCIENCE PROPOSAL

1.1 INTRODUCTION

We propose to measure, to 10% accuracy or better, the absolute trigonometric parallaxes (i.e., the distances) and proper motions (as well as the apparent magnitudes and spectral energy distributions) of a complete sample of the stars brighter than 14th magnitude that lie within 2.5 kiloparsecs (kpc) of the Sun. Using the results of this survey, we will definitively address three key scientific objectives having far-reaching astrophysical and cosmological significance:

- We will provide, for the first time, a definitive calibration of the absolute luminosities of the “standard candles” (the galactic Cepheid variables and the RR Lyrae stars) that are fundamental in defining the distance scale to nearby galaxies and clusters of galaxies;
- We will calibrate, for the first time, the absolute luminosities of the hundreds of solar-neighborhood stars, including Population I and II stars (such as Population H subdwarfs that are representative of globular cluster main sequence stars), thus enabling diverse studies of stellar evolution and other interesting science. In the case of Population II subdwarfs, this will allow the determination of the distances and ages of galactic and extragalactic globular clusters with unprecedented accuracy, and
- From our survey of 10^7 stars within 2.5kpc of the Sun, we will study the kinematical properties of these stars and, in particular, assesses the abundance of dark matter in the galactic disk with much greater sensitivity and completeness than previously possible.

The proposed investigation will also provide a catalog of star positions and proper motions that will meet the need of the United States Department of Defense (DOD) in the next century.

The volume of space included in the survey is large enough to contain significant numbers of all classes of stars found in the Milky Way Galaxy. The survey will thus provide the scientific community with an invaluable and durable resource, not attainable by other currently planned missions, whereby a large number of other significant and fundamental astrophysical investigations can be carried out, beyond the few to be addressed within the immediate scope of the proposed investigation.

To carry out the proposed investigation, we will develop and fly the Fizeau Astrometric Mapping Explorer (FAME), an advanced successor to Hipparcos that is significantly smaller in mass and lower in cost, but capable of higher accuracy and greater efficiency. The proposed mission will serve as a relatively low-cost precursor to future missions such as Astrometric Image Mission (AIM) and Global Astrometric Interferometer for Astrophysics (GAIA).

1.2 OBJECTIVES AND SIGNIFICANT ASPECTS

1.2.1 BACKGROUND

Our most fundamental knowledge about stars (their masses, absolute luminosities, distances, and motions in three-dimensional space) rests ultimately and ineluctably upon direct measurements of the apparent places of stars relative to a frame of reference ideally defined as an inertial rest frame. From such measurements over time, we can derive the trigonometric parallax (the reciprocal of distance measured in parsecs), as well as the proper motion (the annual change in apparent place caused by a stars movement perpendicular to the line of sight). When the speed of motion along the line of sight is also known from spectroscopic measurement, the space velocity of a star is fully defined. In the case of binary stars, this information yields the masses of the components. These parameters are basic to our knowledge of stellar structure and evolution, the structure and dynamics of the Galaxy, and the scale of cosmological distances.

Until relatively recently, trigonometric parallaxes could be measured photographically (with ground based telescopes) to within an accuracy of about ±10 milliarcseconds (mas), corresponding to an uncertainty of 10% at distances of 10 parsecs. The best modem ground-based measurements, using charge-coupled device (CCD) detectors, achieve accuracies of about ±l mas, (Monet et.al. 1992), pushing the limit of accurately known stellar distances out to about 100 parsecs. Hipparcos measures absolute parallaxes to ±l.5 mas, while the ground-based measurements are referred to the background of visible stars several kiloparsecs distant.

Significant refinement [down to errors 1/50th as large, or 20-30 microarcseconds (μas)] in the measurement of relative parallax can be achieved with ground based optical interferometers over small fields of view (FOV). However, when these measurements are converted to absolute parallaxes, the final accuracy is still not better than about $\underline{+}1$ mas because distances and surface characteristics of the not-very-distant background reference stars are unknown. Very high accuracy (10-20 μas) measurements of absolute parallax are achieved in differential radio interferometry over small angles, but such measurements are necessarily limited to relatively small numbers of objects that are near quasars.

Accuracies of 1-10 μas (yielding distances to 10% accuracy from 10 kpc to 100 kpc) would be achieved in the optical measurement of absolute parallax by proposed space missions such as AIM in the United States and GAIA in Europe. These missions will cost several hundred million dollars each, and would logically follow FAME in the middle to later part of the next decade.

At the present time, a survey mission rather than a pointed mission can obtain the greatest scientific return. A survey mission will catalog a very large number of stars ($>10^7$), while a pointed mission of 2.5 year duration will study at most l,000 objects. A survey mission such as FAME will yield knowledge on all stars with excellent statistics, seeing as far in the galactic plane as extinction permits. The large number of stars will also allow corrections for reddening along the line of sight to program stars such as Cepheids and RR Lyrae via cluster main sequence fitting. The resulting data set will revolutionize our knowledge of the basic parameters of stars, the building blocks of galaxies and the Universe. This knowledge will lead to fundamental advances in galactic astronomy and cosmology.

1.2.2 SPECIFIC OBJECTIVES

It is in this context that we see the opportunity for a MIDEX-class mission to make a definitive contribution to the solution of a number of very far-reaching problems in astrophysics and cosmology by providing accurate absolute parallaxes of a complete sample of 10^7 stars out to 2.5 kpc (20 times the current distance limit and 8,000 times the volume of space for ground-based wide-field astrometry and Hipparcos) as shown in Fig. 1-1 and 1-2. This volume is sufficient to contain significant numbers of all classes of stars, including Cepheid variables, RR Lyrae and δ Scuti stars, O, B and A stars, and Population II subdwarfs, as well as star-forming regions such as the Orion Nebula.

Compelling reasons to undertake such a mission at this time can be cited in the context of several disciplines in astronomy and astrophysics. The key objectives we propose to address specifically and definitively in this mission are described in the following subsections.

1.2.2.1 *Fundamental calibration of the absolute luminosities of RR Lyrae stars and Galactic Cepheids, the "standard candles" for measuring cosmological distances.*

The period-luminosity relation for Cepheid variable sun, and the luminosity-metallicity relation for RR Lyrae stars, are fundamental to the determination of distances to the galaxies in nearby clusters and thus, ultimately, to the determination of the expansion age of the Universe (c.f. Madore and Freedman 1991). Despite the fact that these stars have been used as distance indicators for a great many years, their calibration in absolute units is still very much an issue.

Cepheids

Although the slope of the period-luminosity relation for Cepheids is known from observations in the Magellanic Clouds, the zero-point of the relation must be derived from Galactic Cepheids. Such a zero-point derivation is currently uncertain by 10-20%, since the distances of Galactic Cepheids (with the exception of Polaris) are beyond reach of current capabilities for measuring trigonometric parallaxes. Instead, indirect methods for estimating statistical or spectroscopic parallaxes are used (c.f. Evans 1995, 1992a, 1992b; Jacoby, et.al. 1992; Feast and Walker 1987), as well as methods that rely upon fitting the main sequence colors and magnitudes of clusters in which Cepheids are found.

FAME will measure the absolute parallax of a significant sample of Cepheid variables directly, and thereby obviate all of the traditional, intermediate calibrations. Feast and Walker (1987) give a list of cluster Cepheids, and Table 1-1 shows the accuracy that FAME will deliver. With FAME-determined parallaxes, field Cepheids can also be used as primary distance calibrators. This increases the number of calibrators, and provides many more of the long period Cepheids that are of most value in measuring distances. Table 1-2 gives a list of field Cepheids within 1 kpc and the expected accuracy that FAME will provide.

This rich sample of Cepheids with accurate distance determinations will be the basis for a calibration of the Period-Luminosity relation, and for the investigation of possible three-parameter relationships.

Table 1-1. Cluster Cepheid variables.

		Period	Distance	
Star	(day)	<V>	(kpc)	SNR
alpha UMi	3.97	1.99	0.11	184
SU Cas	1.95	5.97	0.26	76
SZ Tau	4.03	6.53	0.59	34
U Sgr	6.74	6.70	0.63	32
V Cen	5.49	6.82	0.67	30
S Nor	9.75	6.42	0.91	22
T Mon	27.02	6.13	1.67	12
H0144972	5.10	8.87	1.69	12
CPD-537400	11.22	8.37	1.69	12
RZ Vel	20.40	7.09	1.72	12
WZ Sgr	21.83	8.03	1.75	11
DL Cas	8.00	8.97	1.79	12
RS Pup	41.39	7.01	1.79	11
RU Sct	19.70	9.4	2.04	10
VY Car	18.93	7.46	2.08	10

RR Lyrae stars

Because of the importance of RR Lyrae stars in measuring distances to globular clusters as well as to galaxies, enormous effort and hundreds of hours of observing time with large ground-based telescopes have been expended in recent years to calibrate the absolute luminosities of RR Lyrae stars by spectrophotometric methods (Carney 1992; Carney, Storm and Jones 1992). Yet these methods are inherently inaccurate and fraught with potential errors. In fact, distances determined from RR Lyrae stars and Cepheids are discrepant at a level of a few tenths of a magnitude in distance modulus (van den Bergh 1995).

A far superior approach, possible at this time, would be to replace, once and for all, all of the indirectly estimated distances of these stars by directly measured absolute trigonometrical parallaxes.

FAME will provide two unimportant components of the calibration of the RR Lyrae distance scale. First, it will measure the trigonometric parallaxes of a number RR Lyrae stars. Second, it will improve and extend the calibration of the field subdwarf stars. Table 1-3 lists the RR Lyrae stars that FAME will measure directly with an accuracy of 10% or better.

Table 1-2. Field Cepheid variables within 1 kpc.

Star	Period (day)	<V>	Distance (kpc)	SNR
Delta Cep	5.37	3.91	0.32	62
eta Aql	7.18	3.90	0.32	62
beta Dor	9.84	3.77	0.34	58
zeta Gem	10.16	3.91	0.42	48
x Sgr	7.01	4.54	0.45	44
DT Cyg	2.50	5.78	0.45	44
FF Aql	4.47	5.38	0.45	44
BG Cru	3.34	5.47	0.45	44
RT Aur	3.72	5.42	0.50	40
kappa Pav	9.08	4.34	0.56	36
W Sgr	7.60	4.69	0.56	36
I Car	35.56	3.74	0.59	34
YSgr	5.77	5.75	0.59	34
TVul	4.43	5.75	0.63	32
V1334 Cyg	3.33	5.85	0.67	30
AHVel	4.23	5.68	0.67	30
AX Cir	5.27	5.85	0.71	28
IR, Cep	2.11	8.60	0.71	28
R Tra	3.39	6.66	0.71	28
U Aql	7.03	6.47	0.77	26
MY Pup	5.70	5.65	0.77	26
U Vul	8.00	7.14	0.77	26
EW Sct	10.00	8.01	0.77	26
S Cru	4.69	6.57	0.83	24
S Sge	8.37	5.66	0.83	24
Y Oph	17.14	6.15	0.53	24
BFOph	4.06	7.28	0.91	22
VCen	5.49	6.82	0.91	22
T Cru	6.73	6.59	0.91	22
TU Cas	9.14	7.65	0.91	22
V636 Sco	6.79	6.66	0.91	22
BB Sgr	6.64	6.99	1.00	20
EU Tau	2.10	8.15	1.00	20
RV Sco	5.47	7.05	1.00	20

Table 1-3. RR Lyrae stars with parallax measurement errors of less than 10%.

Star	Period (day)	<V>	Distance (kpc)	SNR
RR Lyr	3.69	8.57	0.25	80
xz Cet	2.83	9.20	0.38	52
CS Eri	2.05	9.20	0.48	42
MT Tel	2.07	9.28	0.48	42
AE Boo		10.00	0.56	26
UV Oct	3.49	9.79	0.56	27
V429 Ori	3.17	10.00	0.59	24
DH Peg	1.80	9.78	0.63	23
XZ Cyg	2.93	10.53	0.63	16
RR Cet	3.57	10.33	0.63	18
x Ari	4.48	10.48	0.63	16
RZ Cep	2.04	10.31	0.63	18
RX Eri	3.86	10.10	0.67	20
VX Scl		10.50	0.67	15
SU Dra	4.58	10.24	0.67	18
TU Uma	3.61	10.24	0.67	18
SWAnd	2.77	10.76	0.67	12
Vlnd	3.02	10.48	0.71	14
TT Lyn	3.96	10.17	0.71	18
DX Del	2.97	10.26	0.71	16
SVEri	5.17	10.23	0.71	16
DN Aqr	4.31	10.50	0.71	14

1.2.2.2 Fundamental calibration of the absolute magnitudes of Population II subdwarfs

FAME will determine stellar distances in the solar neighborhood to unprecedented accuracy resulting in precise knowledge of the luminosities of all types of stars. Here we discuss the scientific rationale for the study of just one type of star.

Within the volume of space out to a kiloparsec or two lie hundreds of Population II main sequence stars (subdwarfs), having metallicities similar to globular cluster stars. Globular clusters are thought to be the most ancient constituents of the Galaxy, and other galaxies. Their ages are based upon theoretical evolutionary tracks of stars and upon the observed color (or absolute magnitude) at the turnoff from the main sequence in the color-magnitude diagram.

Absolute trigonometric parallaxes, yielding the absolute luminosities of field subdwarfs within 1-2.5 kpc, would thus be fundamental in enabling the accurate determination of the ages of galactic globular clusters with far more reliability and precision than heretofore possible.

Given the requisite absolute trigonometric parallaxes that would be measured in the course of the proposed mission, we will have two independent age-estimation methods for globulars: the absolute luminosity of the main sequence turnoff, and the absolute magnitudes of the horizontal branch stars. Agreement of these two methods would provide a test of the consistency of the theory of the structure and evolution of Population II stars.

The ages of globular clusters are germane to the interpretation of the Hubble time, since the Universe is presumably at least as old as the oldest stars. Recent estimates of the Hubble constant, however, verge upon being in conflict with the estimated ages of Galactic globular clusters.

FAME will provide an improved H-R diagram using stars within 25 parsecs for which interstellar reddening is negligible. This will allow improved distance and absolute luminosity determinations for stars outside the FAME observing program through the indirect method of cluster main sequencing fitting.

FAME observations may be supplemented by spectra for field stars near the line of sight to individual stars of interest such as Cepheids and RR Lyrae, so that accurate reddening can be determined for these important standard candles.

In general, FAME photometry will give apparent color indices which, when transformed by a standard reddening law will yield intrinsic color indices. The differences between these color indices (color excess) can then be combined with the FAME distances to map out the interstellar absorption.

1.2.2.3 Determination of the space velocities of a complete sample of the stars within 2 kpc of the Sun

A catalog of space velocities complete to 14th magnitude would, of course, have a vast number of uses over many years. First, we plan to use this catalog to carry out a definitive investigation of the distribution of mass above, below, and within the disk of the Galaxy, and its variation with Galactic radius in the neighborhood of the Sun. In particular, we will determine the total gravitational surface mass density in the disk near the position of the Sun.

This relates directly, within the volume of space included in the survey, to the long-standing and apparently universal issue of missing mass or “darker matter” implied by dynamical studies of stars in globular clusters and the rotation of galaxies (the “Oort problem”).

The one place where we have a complete inventory of the luminous stars is in the immediate neighborhood of the Sun. From the mass-luminosity relation (determined from observations of binaries), we know the total mass in these stars and hence the total mass density of luminous material in the neighborhood of the Sun. What we do not currently know is the total mass density. If the local mass density were proven to be significantly greater than that of the luminous matter, this would demonstrate the existence of dark matter in the disk. Because disks are formed by dissipation, such dark matter would almost certainly be baryonic. Such a detection of baryonic dark matter would not only be significant in itself, but would be a further clue to the nature of the dark matter, and would greatly constrain our models of external galaxies.

The principal difficulty in resolving the Oort problem has been systematic errors, so that the estimates for the total column density of the disk (Bahcall 1984; Kuijken and Gilmore 1989, 1991; Flynn and Fuchs 1994; Gould, Bahcall and Flynn 1995) differ by a factor of 2. The proposed mission will provide an estimate of the local density of matter (which can be directly compared with the local density of stars and gas) that is essentially free of systematic error.

FAME will address this problem using a sample of stars lying relatively close to the Galactic plane (Ibl<30 deg), and will obtain distances and velocities from parallaxes and proper motions. A study based primarily on proper motions is, to first order, free of systematic errors because the quantity to be determined (w) and the quantity being measured have the same units, l/time.

We will measure accurate proper motions (< 4 km/sec/kpc) to $N \sim 10^5$ early G stars with distance < 500 pc and $|b|<30$ deg. The resulting velocity errors (< 2 km/sec) are small compared to the stellar motions, allowing a measurement of r_0 to a fractional accuracy $\sim g/\sqrt{N} \sim 0.03$ where $g \sim 0.1$ is a geometrical factor.

The G dwarf study will be the anchor point of our attack on the Oort problem, but many other classes of stars can also be used. For example, K giants can be used to probe at much greater distances from the plane (because accurate proper motions and parallaxes can be measured for these stars at much greater distances). In addition, F and A stars can give a very detailed look at the mass distribution close to the plane because of their low velocity dispersions.

F and especially A stars ordinarily cannot be used for the Oort problem because they are not old enough to be phase-mixed in their vertical orbits. However, since the FAME sample covers the whole sky, the phase inhomogeneities of many unconnected subsamples will tend to cancel, permitting the use of these stars for the first time.

1.2.2.4 Other Science

Apart from these key objectives, the data collected will serve as an invaluable resource in the public domain that will inevitably bring significant progress to other fields of astronomy that are of wide interest and fundamental importance.

For example, stellar models require accurate observational constraints on stellar luminosities, masses, and radii as input. The accuracy required for luminosity is ~1%, for which parallaxes must be known to 0.5%. FAME will measure parallaxes to 0.5% accuracy for stars brighter than 12^{th} magnitude in a sphere of 20-pc radius.

FAME will reach 1% relative precision for the luminosities of a sizable number of main sequence A and F stars. This group is especially interesting because it includes the transition from radiative to convective energy transport in the outer envelope, and many stars with peculiar characteristics such as Ap and pulsating δ Scuti stars. With metallicities obtained by spectroscopy, very precise determination of the luminosity will allow fundamental parameters to be derived, such as the depth of the convective zone and the efficiency of convective transport. For cooler stars, precise luminosities will place strong constraints on other fundamental parameters, such as the equation of state and molecular opacity.

At a 5% level of accuracy, the distance horizon will include rarer but important types of stars, such as O stars, supergiants, T Tauri stars, Cepheids, and RR Lyrae-type stars.

Our knowledge of stellar masses derives mainly from the analysis of binaries. FAME will determine Parallaxes and relative positions of the components of binaries, thus contributing significantly (in terms of accuracy and the number of binaries with known orbits) to the determination of stellar masses. Through analysis of the positions of photocentric emission and the use of multiple colors, FAME will likewise determine the masses in unusual systems such as those containing white dwarfs and black holes.

FAME will provide accurate parallaxes for determination of absolute dimensions in the cases where angular sizes are known. Only a few accurate radii are presently available for testing stellar models, the best of these coming from the analysis of eclipsing variables. Ground-based interferometry and lunar occultation techniques typically measure angular radii to accuracies in the range 0.2 to 2.0 mas. Future ground-based instruments, such as the Navy Prototype Interferometer, will have the capability to measure stellar diameters and shapes (and their time variation) to 0.1 mas.

Likewise, FAME will contribute fundamentally to calibrating the distances of open star dusters, determining the absolute color-magnitude diagrams of newly-formed star clusters, and identifying candidate stars for the possible detection of planets. Also of likely interest will be measurements of' the gravitational bending of starlight by Jupiter, Saturn, and the Sun, allowing the post-Newtonian deflection parameter to be determined significantly better accuracy than currently available.

1.3 INVESTIGATION APPROACH

The Hipparcos project was the first astrometric survey ever conducted without the limitation of Earth's atmosphere. It measured more than 100,000 stars to an absolute accuracy of 1 mas and had a magnitude limit of V=12. Through improvements in technology, FAME will dramatically improve upon the sensitivity and accuracy of Hipparcos. Measuring over 10 million stars to better than 50 μas ($V < 9$) and having a magnitude limit of V=16, FAME will expand the measurement space by over three orders of magnitude (see Fig. 1-1).

Much like Hipparcos, FAME is based on the use of a telescope that looks at two FOVs separated by a fixed basic angle (89 deg). The spacecraft rotates at a rate of once every 2.5 hours and measures stars along a great circle. The rotation axis of the spacecraft precesses slowly (6 times a year) to scan the whole sky. Unlike Hipparcos's image dissector tube, FAME will use a modem CCD array with high quantum efficiency to simultaneously measure the transit times of many stars. The CCDs will be used in a time-delayed integration mode to synchronize the readout with the rotation of the spacecraft. A laser metrology system will be used to monitor the basic angle of the instrument, as opposed to simply relying on its thermo-mechanical stability. Development of laser metrology systems of this kind will be critical for many future astrophysics missions (e.g., AIM). A low-dispersion prism spectrometer is used to measure the star's photometric information. Modem instrumentation coupled with advances in the design and construction of low-cost, lightweight spacecraft will make FAME a very inexpensive mission with high science return. The FAME mission concept, instrument, and spacecraft are discussed in more detail in Section 2. Figure 1-3 shows the spacecraft and instrument in the launch shroud.

Table 1-4, Expected performance.

Magnitude	Accuracy (μas)
5	21
7	25
9	43
11	101
13	2*70*
15	797

An input catalog will be generated by the science team using data from the Washington Fundamental Catalog and other catalogs from the United States Naval Observatory (USNO). The catalog will be loaded onboard the spacecraft and will be re-programmable from the ground. Over the course of the 2.5-year mission, each of the program stars will be scanned multiple times in different directions. The data from all the targets will be analyzed together in order to derive their positions, proper motions, and parallaxes, as well as to solve for instrument parameters such as the basic angle. The data will be analyzed using procedures and algorithms similar to those used in the Hipparcos data reduction, as discussed in Section 4.

Table 1-4 lists the predicted astrometric accuracy for FAME. The accuracy has three components: systematic errors, detector read noise, and photon noise. Systematic errors, arising from instrument limitations (such as pixel variations) will limit performance for bright stars. We have calculated a systematic error floor of 20 μas which we discuss in more detail in section 2.1.3.1. For faint stars, the dominant error source is 5e^- CCD read noise. Between these extremes, the dominant error source for stars between 7th and 14th magnitude will be photon noise. Systematic errors, arising from instrument limitations (such as pixel variations) will limit performance for bright stars. We have calculated a systematic error floor of 20 μas which we discuss in more detail in Section 2.1.3.1. For faint stars, the dominant error source is 5e^- CCD read noise. Between these extremes, the dominant error source for stars between 7th and 14th magnitude will be photon noise.

1.3.1 Potential Extended Mission

The baseline mission described in this proposal is for a 2 -5-year lifetime. However, there are some significant advantages to extending the mission lifetime. Increasing the mission length will increase the number of observations on the target stars and the resulting astrometric accuracy. Position and parallax measurements will improve as the suare root of the mission length, whereas proper motion measurements would improve as the 1.5 power of the mission length, thereby producing a catalog whose star positions are accurate for a longer period of time. Since this catalog is important for DOD applications, operations for an extended mission would be paid for by the Navy.

Other advantages of an extended mission would be for investigations that would require data measured over periods longer than 2.5 years. One such example, is the detection of unseen companions with periods greater than mission lifetime. A Sun-Jupiter system at 100 pc would exhibit a peak-to-peak astrometric signature of 100 μas and be detectable by an extended FAME mission.

1.3.2 Minimum Science Mission

The FAME science team has determined that the science return from a mission which has an astrometric accuracy half that shown in Table 1-4 would remain compelling and exciting. With an accuracy of 80 μas for 9th magnitude objects, the number of Cepheids that could be measured to 10% would decrease from 20 to 5. Though a serious impact to this science objective, FAME will still provide the first direct absolute parallax measurements on these targets. For RR Lyrae stars, the impact is less; half of the objects in Table 1-3 can still be measured to 10% accuracy.

Although a minimum science version of FAME will still measure 10 million or more stars, decreasing the performance by a factor of two will reduce the volume of stars for a given accuracy by a factor of 8. Our survey would still exceed previous capability by a factor of 10, measuring stars accurately within a 1 kpc radius. Again, this would result in poorer statistics in the study of Population II subdwarfs and other classes of stars. However for all but the rarest stellar types, the sample will still contain an abundant numbers of stars.

The Step 2 proposal will contain a preliminary descope plan to the corresponding minimum science performance.

1.4 SCIENCE TEAM

The 15-member science team whose leadership will assure the scientific productivity of FAME is composed of distinguished international experts in astrophysics, galactic and extra-galactic astronomy, stellar evolution, cosmology, ground-based and space-based astrometry and interferometry, and space instrumentation. The Principal Investigator is the Scientific Director of the United States Naval Observatory.

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2.0 TECHNICAL APPROACH

2.1 MISSION OPERATIONS CONCEPT AND REQUIREMENTS

We have endeavored to design the Fizeau Astrometric Mapping Explorer (FAME) mission to be simple, yet powerful. Science data is obtained using a single observing mode, and there are no moving parts or deployments. FAME draws extensively upon the successful experience of the European Hipparcos mission (flown in 1989), while pioneering powerful new optical techniques. By employing modern charge-coupled device (CCD) detectors, and a novel optical design, FAME will produce data with 2O times better precision on 60 times more sources than Hipparcos. The FAME satellite is depicted in Figure 2.1.1.

2.1.1 Mission Design

21.1.1 Scan Strategy

FAME will scan the sky for 2.5 years, using the same strategy successfully demonstrated by Hipparcos. The concept is depicted in Figure 2.1-2. The entire satellite is placed into a slow roll, with one revolution being completed every 23 hours. A telescope views the sky with its line-of-sight at a 90-deg angle to the axis of rotation. As the satellite rotates, the telescope scans a great circle strip across the sky, the strip closing upon itself after one complete revolution. A beamsplitter permits the telescope to simultaneously view two separate fields of view along the strip. The two fields are separated from each other by an angle of 89 degrees, referred to as the *basic angle*. Thus, at any moment during the scan, two fields of view are simultaneously imaged on the focal plane of the instrument. As in the case of Hipparcos, the basic angle was chosen to maximize the rigidity of the astrometric solution.

To cover the entire sky, the rotation axis of the satellite is set at a 45 deg angle to the satellite-Sun line, and is slowly precessed about this line (Figure 2.1-3a). One full precession of the rotation axis requires 60 days. This simple two-axis motion—rotating slowly about an axis that is precessed about the satellite-sun line—results in a scan pattern that provides uniform all-sky coverage over the course of a year. Figure 2.1-3b shows the scan pattern over one complete precession of the axis (60 days). The scan also observes targets at nearly orthogonal directions, important in measuring both components of star position.

2.1.1.2 Harvesting the Data

The telescope produces images of stars on ten large-format CCD focal plane arrays, as depicted in Figure 2.1-4. Data are acquired using a technique known as *time-delayed integration*, whereby the photoelectric charge in the CCD is clocked in synchronization with the moving image as it scans across the array. The image continually reads out as it “spills” off the edge of the device. Synchronization of the CCD clock rate with image motion is assured by means of a rotation rate sensor, and two additional CCDs (identical to those in the science arrays), which are used to time the passage of bright stars. The clocking rate of the CCDs is adjusted in real time once a minute in order to maintain synchronization. Star images are thus sampled, time-tagged, and transmitted to Earth where they are ultimately centroided and processed with the remaining observations to produce a catalog of positions, proper motions, and parallaxes for 10 million stars.

2.1.1.3 On-Board Data Processing and Storage

On average, only 34 program stars will fall on the science array at any given moment. This means that most of the raw data read from the CCDs are of no interest and can be discarded. The instrument computer uses the on-board input source catalog to window the data in real time, retaining only the images of the program stars. We will retain a window of 50x50 pixels surrounding each image. After 2-to-l lossless compression of the windowed data and 4-to-1 on-chip binning in the cross-scan direction, the average data rate is reduced to 50 kbits/sec. One full 24-hour period of data collection produces 500 Mbytes of data that are stored on board the spacecraft for later transmission to Earth. The spacecraft data storage capacity is 3.2 Gbyte, which is enough to store approximately 6 days worth of data.

2.1.1.4 The Orbit

Several competing factors were balanced in selecting the FAME orbit: the need for an unobstructed view of the sky, a stable thermal environment, for a simple telecommunications and orbit-determination strategy, and efficient use of the launch vehicle. We propose an elliptical high-Earth orbit for FAME, having an apogee of 200,000 km and a perigee of 30,000 km (as measured from Earth's center). FAME will have an orbital period of 5 days.

The orbit apogee is close enough to Earth that data may be returned using omnidirectional antennas. This simplifies the telecommunications strategy and enhances observing efficiency by avoiding the need to reorient the spacecraft to aim a high-gain antenna at Earth. Uninterrupted observing proceeds throughout the telecommunication period. The elliptical high-Earth orbit has the added advantages of being relatively robust against orbit-injection errors, and requiring no orbit maintenance.

2.1.2.5 Telecommunication Strategy

Telecommunication is accomplished using an S-band transponder, on-board omnidirectional antennas (see Section 2.3.1.3), and DSN ground stations (see Section 2.3.3). Two 2-hour communication links are required each day, 8 to 12 hours apart. One hour of each link is also used for Doppler ranging. Simultaneous communications and ranging is possible during this time; however, the data rate during ranging is limited to a maximum of 128 kbits/sec. During the remaining hour of each 2-hour pass, data rates of up to 1.024 Mbits/sec are used for telecommunications when the link margins are greater than 3 dB (see Table 2.1.1).

The FAME telecommunications architecture utilizes the 26-m DSN antennas for regular operations. The large-capacity on-board solid-state data recorder provides flexibility in scheduling all telecomm events and can buffer up to 6 days worth of instrument data. The 34-m DSN antennas will be used intermittently (once per week) to provide additional transmit capacity and operational flexibility for the system. Additional scheduling flexibility can be provided by using the existing Navy-owned-and-operated Pomonkey ground station (an S-band, DSN-compatible, 30-m dish).

Table 2.1.1. Link margin summary table for 26 m antenna.

		Link Margin at Elevation Angle					
Altitude (km)	Data Rate (Mbit/sec)	5 deg (dB)	10 deg (dB)	20 deg (dB)	40 deg (dB)	60 deg (dB)	90 deg (dB)
35,000	1.024	4.2	4.9	5.5	6.1	6.5	6.7
65,000	0.256	5.3	6.0	6.4	6.9	7.1	7.2
110,000	0.128	4.2	4.8	5.2	5.5	5.7	5.8
150,000	0.064	4.4	5.1	5.4	5.7	5.9	5.9
180,000	0.032	5.8	6.5	6.8	7.1	7.3	7.3
200,000	0.032	5.3	6.0	6.3	6.6	6.8	6.8

2.1.1.6 Orbit Determination

Orbit maintenance is not required because the high elliptical orbit is stable under gravitational and other perturbations. Mission operations requires that navigation be sufficient for tracking and telemetry, which is easily met. However, science data analysis requires that the orbit be reconstructed with a velocity accuracy of at least 2 cm/sec during all observations. This is accomplished for FAME by tracking twice a day for 1 hour and using Doppler and ranging data from DSN ground stations. The exact times of these tracking passes are not important, allowing the DSN some schedule flexibility. The tracking passes will be performed as part of the telemetry downlink, using the 2-way transponder to combine range and Doppler signals with the science data.

2.1.1 Launch Vehicle and Orbit Insertion

A Delta-Lite launch vehicle (LV) configuration consisting of 2.9-m fairing, a Star 37 upper stage, and two Castor IVB strap-on motors is well suited to the FAME mission. We have been informed by the Goddard Space Flight Center (GSFC) Mission Analysis and Integration Manager that such a configuration will place 632 kg into the FAME transfer orbit described below. FAME's total mass is 418 kg (including a Star 17), providing a 214 kg (51% of flight system) mass margin.

The launch vehicle delivers the spacecraft into a 28.7-deg highly elliptical orbit (185-km perigee, 200,000-km apogee). The FAME spacecraft and upper stage are despun to a nominal spin rate using LV-provided capability. The spacecraft is subsequently separated from the Star 37 motor using a V-band separation system. The attitude is trimmed with the onboard cold gas system to provide adequate solar array illumination based upon the case attitude determination system (Sun sensors and gyro). Approximately 2 days later as the spacecraft nears apogee, the vehicle attitude is adjusted for the next ΔV maneuver and spun-up using the cold gas system. The Star 17 motor is fired to raise perigee to 30,000 km and then jettisoned using a second V-band separation system. In both separations, methods are used to prevent recontact. The spacecraft spin rate is reduced to the operational mapping rotation rate and oriented so that the rotation axis is 45 degrees relative to the Sun vector using the coarse attitude determination sensors and cold gas system. Attitude control is handed off to the fine pointing attitude determination system (star tracker and gyro) before the mapping portion of the mission begins.

2.1.3 System Level Requirements

2.1.3.1 Astrometric Accuracy

FAME will have the astrometric accuracy shown in Table 1.8. These performance numbers are based on a systematic error floor of 20 μas whose error budget is shown in Figure 2.1-5. The dominant sources of systematic error are residual uncertainty in the spacecraft rotation and thermal/mechanical instability of the optical train. The rotation angle of the spacecraft is determined during data analysis from:

- the time-tag on each image generated by the spacecraft clock
- the rotation rate measurements from the measurement rotation rate sensor, and

- the measured changes in the basic angle of the instrument.

The thermal/mechanical stability requirement addresses alignment errors that are not measured by the on-board telescope metrology system. These unmeasured errors are minimized by maintaining FAME's optical system in a stable thermal environment.

A concern for stellar aberration must be applied to the data to account for the velocity of the spacecraft relative to the positions of the target stars. This correction sets the orbital velocity knowledge requirement of 2 cm/sec which is available for the FAME orbit with current technology.

FAME's predicted astrometric performance also assumes a point-spread function visibility of 0.66. Degradation in this visibility arises from systematic sources such as pixelation, distortion and wavefront error in the optical system, finite CCD modulation transfer function (MTF), as well as from smearing of the image due to imperfect synchronization in the time-delayed integration across the CCD. In order to minimize the effects of image smear, we require that there be no more than 1/3 pixel of relative motion between the docked charge in the CCD and the true motion of the image during the entire 2.5 seconds required for the image to cross the CCD. The instrument's rotation-rate sensor monitors the true rate of rotation and updates the CCD clock rate. The above errors have been modeled and their equivalent point-spread function penalties are represented in the error budget shown in Figure 2.1-6.

2.1.3.3 Spacecraft Pointing Requirements

The spacecraft must meet four pointing requirements.

- Stars must scan across the CCDs with less than 70 μm of cross-scan motion during the 2.5 seconds required for images to cross the array. This preserves photometric accuracy and requires that the transverse angular rate of the spacecraft be less than 0.30 arcsec/sec.
- There must be a minimum of 50% overlap between the beginning and ending of a great circle scan. This requires that the axis of rotation of the spacecraft be inertially stable to within 15 arcmin.
- The absolute rotation rate of the spacecraft must be maintained within ±5% of its nominal value so that the CCD clock rate will remain within its adjustment range.
- The rotation rate of the spacecraft must vary less than 1 in 12,000 (1/3 of a pixel) during the time required to update the rotation rate (-l min).

During the celestial mapping phase, the number of thruster firings must be minimized during the 2.5 hour scan period. This directly imposes constraints on the vehicle inertias, the location of the center of pressure (CP) with respect to the center of mass (CM), and the controller design. Solar pressure will induce perturbations to rotation dynamics of the spacecraft. This effect is minimized by FAME's axisymmetric design and by constraining the CP-CM offset to less than 5 mm. Even though our orbit perigee is 30,000 km, gravity gradient torques still induce large perturbations. To minimize them, we require FAME to have the following mass properties:

- products of inertia less than 2% of the minimum moment of inertia and
- principal moments must be within 2% of each other.

These requirements make the spacecraft as close to a dynamically balanced sphere as possible. All these constraints must be met over the 2.5-year design life of the mission.

Corrections to the vehicle rate during observation will be small. The transverse rate correction impulses will perturb the star image by less than 7 mas in the rotation direction and 3 μas in the transverse direction, while a rotation-rate correction perturbs the image by less than 100 μas in the spin direction.

2.1.4 Block Diagram and Component List

A block diagram for FAME is depicted in Figure 2.1-7. The number of interfaces between the instrument and spacecraft has been minimized, as discussed in Section 2.2.8. Table 2.1-2 lists FAME’s major components, together with power and mass estimates**.** Note that the FAME design shows a 51% mass margin and a 31% power margin.

Table 2.1-2 FAME Manifest

		Power (W)	
	Mass (kg) (kg)	Peak	Average
Instrument			
Optics & mount	23		
Camera head	10	60	60

Relay tower	7		
Optical bench	15		
Electronics shelf	10		
Electronics	30	60	60
Thermal hardware	5	30	30
Fasteners. Etc.	5		
<u>Spacecraft</u>			
S/C controller	8	46	22
Solid state data rec.	9	30	30
Telecom	6	20	5
Solar array	3		
Battery	10		
Power distribution unit	7	10	10
Star tracker	13	12	12
Gyro	5	30	30
Sun Sensor	5	1	1
RCS hardware	43		
Propellant	18		
Thermal control	10	80	8
Structure	34		
Ballast	23		
Harness	20		
<u>Booster</u>			
Adapter	14		
Star 17 SRM	82		
Ordinance control	5		
Instrument subtotal	104	150	150
Spacecraft subtotal	213	229	118
Flight system total	317		268
Booster subtotal	101		
Total	418		268
Delta Lite Capability		Solar Array	
(29-m fairing, two Castro-IVB.and Star 37 SRM)	632	Design	350
Margin on flight system	214 (51%)		82 (31%)

2.1.5 Mission Operations

Mission operations will be performed using the GSFC Mission Operations Center. Operation of the FAME mission is particularly simple for the following reasons:

- FAME is an all-sky-survey mission using a single observing mode,
- telecommunication occurs without the need to perform any attitude maneuvers, and
- the spacecraft and instrument operate autonomously throughout the entire mission.

We believe that FAME's mission operations requirements are completely compatible with the GSFC mission operations baseline capability listed in Appendix C of the Announcement of Opportunity, with the exception of navigation. The Jet Propulsion Laboratory (JPL) will perform the navigation function for FAME which has been included in our cost estimate. United States Naval Observatory (USNO), Naval Research Laboratory (NRL), and

JPL plan to contribute personnel to the GSFC mission operations team to support mission-peculiar operations needs, such as quick-look data analysis, and anomaly resolution.

Upon initiation of the observing mode, the spacecraft will determine the desired attitude based on the time of year. Once the spacecraft attitude-control system (ACS) has achieved its commanded orientation and rotation rate, the spacecraft computer instructs the instruments to begin observations. The instrument receives ACS information and extracts the upcoming star list from the on-board catalog. The instrument autonomously begins its own attitude sensing and rotation-rate determination. Once the instrument is initialized, data are taken and relayed to the spacecraft computer where they are stored in the spacecraft memory in preparation for downlink. Because FAME uses omnidirectional antennas, no reorientation is needed during transmission—observation can continue during the downlink period. The operations team will perform quick-look analysis of the data to ensure that the mission is operating properly.

2.1.6 Science Operations

Because of FAME's single-observation mode and autonomous operation, science operations responsibility is minimal. The Science Operations Center at USNO will:

- monitor the quality of FAME data and sky coverage throughout the mission life and
- archive the data and distribute it to the analysis team.

In addition, the Science Operations Center can request a change of the on-board star catalog during the course of the mission.

2.1.7 Method and Procedures for Project Phases

Immediately upon selection, the FAME team will begin detailed definition of project requirements and preliminary design of instrument and spacecraft subsystems. USNO, JPL, and NRL have already established a close working relationship during preparation of this proposal and we anticipate a smooth transition into Phase I definition. The team will also begin detailed discussions with GSFC on mission operations launch vehicle integration and mission assurance. The design, integration, operations flow, and expected products and end items associated with each phase will be discussed in the next subsection. Section 4 details the Management Plan.

2.1.7.1 Phase I

Phase I will be characterized by a fast-paced systems-oriented preliminary design of the FAME instrument, spacecraft, and ground system. Requirements and interface definition will be emphasized. Phase I will include the Systems Requirements Review (SRR) and the Preliminary Design Review (PDR). All long-lead procurement items, such as the focal-plane CCDs and the optics substrates, will be identified. Risk mitigation plans will be defined. All risk win be sufficiently retired by the end of Phase I so that a decision to proceed with FAME can be made with confidence. End items and deliverables for Phase I include:

- Development Plan
- System Concepts and Operating Plan
- Descope Plan
- Risk Retirement Plan
- Performance Assurance Program Plan
- Public Outreach Plan
- Level 1 Requirements Definition
- Interface Control Document
- Phase III and IV Proposal
- Definition Phase Final Report
- GSFC Support Task Definition

2.1.7.2 Phase II

Phase II will develop a detailed design. Long-lead procurements will be initiated. Risk retirement demonstrations will be completed. The team will revise the baseline design in preparation for a Critical Design Review (CDR).

2.l.7.3 Phase III

Phase III will complete the development phase, launch, and in-orbit checkout of the FAME satellite. This phase will include the CDR, Test Readiness Reviews, System Acceptance Review, and Launch Readiness Review.

After the instrument payload development is completed at JPL, the instrument will be delivered to NRL for integration with the spacecraft. A support team will accompany the instrument and collocate with the NRL team for the remainder of the integration and test flow. System level testing—including compatibility checks with the ground segment—will be performed at NRL. The FAME satellite will be transported to Kennedy Space Center (KSC) for integration with the launch vehicle. Following launch, an in-orbit checkout will be performed.

USNO will develop the ground analysis system. NRL will work with GSFC to produce all required operations documentation. End items and deliverables for Phase III include:

- Instrument Payload
- Spacecraft
- Science Operations Center
- Data Analysis Center
- Mission Specific Ground Support Equipment
- Operations Handbook
- End Item Data Packages
- In-Orbit Calibration Report

2.1.7.4 Phase IV

Data will be collected by the FAME mission for 2.5 years and analyzed to produce a catalog of position, proper motions, and parallaxes for approximately 10 million stars. The catalog will be released in stages to the scientific community as data reduction proceeds so science analysis can proceed in parallel with catalog generation. End items and deliverables at the end of Phase IV (4 years after launch) include:

- FAME Archival Star Catalog
- Scientific Findings of Proposed Investigation

2.2 FAME INSTRUMENT

The FAME instrument payload is shown in Figure 2.2-1. The instrument consists of an optical telescope that produces stellar images, a camera to detect the images, and electronics to record and compress the data before they are passed to the spacecraft for storage and later transmission to Earth. In addition, the instrument electronics provide temperature control and report diagnostic information. Table 2.2-1 summarizes key instrument parameters.

2.2.1 Optical Subsystem

Figure 2.2-2 depicts FAME's optical train. The beamsplitter consists of two glass plates mounted to an optically flat silicon-carbide frame. Three metering rods maintain proper alignment between the beamsplitter and the primary mirror. The next six optical elements correct wavefront error and distortion across the 0.49x0.1-deg field of view. A 150-element error budget was used to determine that the as-built system will be diffraction limited at a wavelength of 0.5 μm, with 3 μm root mean square (rms) of distortion across the entire field—required to ensure that images do not smear as they integrate across the CCD. The optical design is a rotationally symmetric (apart from the fold flat) on-axis design with the focal plane offset from the center of the image plane. The optical train is folded so that the focal plane is located near the centerline of the satellite to facilitate passive cooling of the CCD array. Table 2.2-2 summarizes design parameters for the optical elements. We have discussed the optical design with two leading optics vendors and are confident that the components are well within the state of the art.

Table 2.2-1. Instrument Summary.

Volume	1x1.2x1.3m
Mass	104 kg
Power	
Safe mode	23W
Operational	150W

Data rate	50 kbits/sec

Figure 2.2-3 shows a simulated star image. Because high-resolution information is contained only in the scan direction (long dimension of telescope), rectangular CCD pixels were chosen. The core of the star image at O.5 μm is sampled in the scan direction by a minimum of four pixels. To enable spectrophotometry of the sources, starlight is dispersed in a direction orthogonal to the scan direction by introducing a slight wedge to the beamsplitter.

2.2.2.1 Optical Alignment

Optical alignment of FAME will draw upon our recent experiment with the Wide-Field and Planetary Camera-2 (WFPC-2), which corrected the Hubble Space Telescope's (HSI) spherical aberration.

Independent, absolute testing of the components at the vendor will ensure that the mirrors meet their requirements. Likewise, the optical alignment will rely upon early and redundant testing of key parameters to ensure timely delivery of the optical subsystem. The optical train is conveniently divided into two parts: the on-axis telescope (beamsplitter, primary, secondary, and fold mirror) and the relay (all the other mirrors). These two parts will be aligned in parallel using different techniques. The telescope alignment will use conventional double-pass interferometric testing over the full 60- x 20-cm aperture to verify the wavefront. Testing in autocollimation does not require a null lens, as the telescope is well-corrected on-axis. Furthermore, this technique measures the wavefront that drives the telescope tolerances.

Table 2.2-2. FAME optical parameters in the cases where the parameters along the scan axis differ from those in the cross-scan axis, the along scan parameters are given first.

Aperture size	60x20
Collecting area	1000 cm^2
Focal length	3600 cm
Field of view	0.10x0.49 deg
Pixel size	1.5x30 μm
Plate scale	86x172 mas
Spectral range	0.5-0.90 μm
Spectrometer resolution	8
Optical surfaces	Beamsplitter - Wedged
	Pri. Mir. – parabola
	Sec. Mir. – hyperbola
	Relay Opt.
	ellipse. sphere
	sphere. ellipse
Design Residuals	
Distortion*	300 nm rms across field
Wavefront error	4 nm rms
*Deviation of image centroid from a perfect f-θ scan.	

The relay tolerances, on the other hand, are driven by distortion. Here, we propose using a coordinate measuring machine to align the mechanical axis of the relay mirror segments (the optical figure and mechanical axis are registered by the mirror manufacturer to 70 μm). This greatly simplifies the alignment, which has relatively loose tolerances, decenters of 100 μm, and tilts of 20 arcsec. (These are at least a factor of 2 looser than those on the successful WF/PC-2.)

After focusing and boresighting the relay and the telescope, the entire optical system will be tested using a single calibrated test CCD and an optical stimulus with a scan mirror to simulate the spacecraft rotation. The test CCD can be operated at room temperature and moved in the focal plane to avoid having to fill the entire focal plane with CCDs during these telescope tests. Phase retrieval—first used to determine the HST prescription—will be used to analyze the data. To verify optical subsystem performance, we will perform a double-pass interferometric test of the wavefront in a thermal vacuum, shake the subsystem, and repeat both the thermal test and the ambient distortion test. A fully qualified subsystem is then delivered for system integration.

2.2.1.2 Telescope Metrology System

FAME, as well as all other future optical systems with similar levels of precision, requires a laser Metrology system. The FAME metrology system, shown in Fig. 2.2-4, monitors the basic angle of the instrument (the angle between the beamsplitter and the optical aids of the telescope). A 1.3-μm Nd:YAG solid-state laser is launched from a fiber collocated with the CCDS. The laser light illuminates the beamsplitter element and is retroreflected via low amplitude phase gratings that have been inscribed on the ends of the beamsplitter. Since there is a difference in the optical path between the light incident on the two beamsplitter ends, the interfered intensity will be a function of the laser frequency. Varying the laser frequency with acousto-optic modulator over a range of 300 MHz will produce an entire intensity cycle whose phase will vary as the distance between the two beamsplitter end points change. By sampling the intensity cycle at four frequencies (75, 150, 225, and 300 MHz) and computing its phase, the angle of the beamsplitter is monitored.

Accurate angular measurements at the 25 μas level require distance measurements with 50-pm accuracy, which require laser stability of 5 parts in 10". To accomplish this, a Zerodur Fabry-Perot cavity is used. A portion of the laser light is fed into the Fabry-Perot cavity which serves as the frequency reference. The reflected light is measured and the laser frequency is servoed to it to the null of the Fabry-Perot reflectance. This method has demonstrated laser stabilization to 1 part in 10^{11}.

Considerable effort is currently underway to space qualify the metrology components and systems for other NASA programs. A metrology laser suitable for FAME is currently being qualified by both the New Millennium program and the Troposphere Emission Spectrometer (TES), an Earth-Observing Satellite instrument. New Millenium is also testing an acousto-optic modulator that may be suitable for FAME. For FAME, we have costed an independent qualification program for the metrology components and system. If the funding for the above programs continues as expected, FAME's qualification program will be descoped with the savings returned to the management reserve.

2.2.3 Focal-Plane Camera

The focal-plane camera represents one of the major advances of FAME over the Hipparcos mission. A large-format CCD is placed across the focal plane spanning a field of view of 0.49 x 0.10 degrees, as shown in Fig. 2.1-4. The science array consists of ten individual 4096 x 1024 two-side buttable CCDs arranged in a strip. These devices are minor modifications to an existing 4096 x 2048 detector manufactured by SITe, which is planned for use in the HST Advanced Camera in 1997. By basing the FAME CCD on the Advanced Camera device and focusing resources at a single foundry, we lower the risk to both programs, and assure that the highest performance devices will be available for future astrophysics programs. Two more CCDs (identical to the science array devices) are used as the rotation-rate detector; each has four output amplifiers for low noise operation. Because the device is clocked for time-delayed integration, the amplifiers must be located along one edge of the chip. Moving the readouts to the side of the array and changing pixel shape from square (15 x 15μm) to rectangular (15 x 30μm) are the only modifications to the Advanced Camera device, shown in Figure 2.2-5. We will use the standard antireflection coating that results in quantum efficiency exceeding 0.75. To mitigate radiation-induced performance degradation, the CCD will be passively cooled to –70° C and shielded with 1 cm of tungsten. Table 2.2-3 summarizes the CCD specifications.

Table 2.2-3. FAME CCD specifications.

Format	4096x1024.backside illuminated
Pixel Size	15x30 μm
Process	3-Phase, MPP.LDD
Amplifiers	4 on-chip buried channel detectors
Quantum Efficiency	>0.75 at λ = 600nm
Noise	<5e$^-$ rms
Dark Current Gen	<0.2 nA/cm^2 at 22C
Line Transfer Time	<100 μs
Array Flatness	<20 μs
Nonlinearity	<1% over dynamic range
Clock Rate	2 MHz to output well
Charge Tranfer Eff	>0.00000
Full Well Capacity	2000.000 e$^-$ (vert.) 8000.000 e$^-$ (horiz)

The camera subassembly, shown in Fig. 2.2-6, includes the camera head and the signal channel electronics. The design is modular, permitting easy replacement of individual CCDs if necessary. The composite facesheet/honeycomb panel construction of the camera head provides for a stiff CCD mounting structure. The CCD mount is thermally isolated from the rest of the relay structure. For low noise operation, the signal chains are mounted close to the CCD, but are thermally isolated from the camera head by means of a fiberglass honeycomb standoff panel, and Multi-Layer Insulation (MLI). A50-cm-diameter composite aluminum radiator cools the CCD and is thermally strapped to the CCD mounting structure.

2.2.4 Instrument Electronics

The FAME instrument electronics, shown schematically in Fig. 2.2-7, perform three tasks. The first is to provide realtime attitude information of the instrument optical axes by centroiding bright stars (<10 mag) and comparing their measured positions to the on-board catalog. This task is performed by the R-6000 instrument computer, along with data sorting, appending headers, and instrument bus control.

The second task is to window the data coming from the camera to reduce the amount of data downlinked. Widowing is accomplished by synchronizing the scrolling input catalog stored on-board with real time attitude information. During the instrument acquisition phase, a window larger than the spectrally dispersed image (50 x 50 pixels) will be used. As improved information about spacecraft attitude and rotation rate is derived, the window can be narrowed. Windowing is accomplished by twenty 8051 microprocessors, each operating on two signal chains.

The third task for the instrument electronics is to measure the rotation-rate of the satellite by timing a star crossing on the rotation rate CCDS. This operation will be performed only on 10th magnitude stars and updates the CCD clock rates every 52 seconds. A separate 8OC86 microprocessor will be dedicated to performing this task. The rotation-rate information will be used to control a direct digital synthesizer and hence the clock rate of the CCD. In addition, this rate will be used to synchronize the instrument and spacecraft power supplies.

2.2.4 Thermal Subsystem

FAME is configured such that the instrument is always in the spacecraft's shadow to provide a stable environment. The thermal design for the FAME instrument must provide the following:

- CCD detectors that are stable to 10 mK with a nominal temperature of -70° C (± 5°), and
- optics that are stable to 3 mK with a nominal temperature of 15° ± 5 C.

The operating point of the detector and instrument is not critical, but once in operation, the temperature must remain stable over one 2.5-hr rotation period. Less than a 3 mK rms change in the temperature gradients of the optical bench is required. This is accomplished by the following steps:

- isolating the instrument from direct solar input,
- minimizing the heat input from the spacecraft with MLI,
- removing heat from instrument heat sources (e.g., electronics) using radiators, and
- placing the entire instrument in an aluminum tent and using heaters to control the temperature.

The detectors are passively cooled using a radiator located at the top of the spacecraft with a direct view to space. The aluminum radiator measures 0.2 m^2. Fiberglass standoffs insu1ate the detector from the rest of the instrument.

A 100-node thermal model demonstrates thermal gradients of less than 3° C and temperature stability of better than 3 mK during a one rotation period (see Fig. 2.2-8).

2.2.5 Mechanical Subsystem

The structural subsystem is composed of three subassemblies: telescope bench, relay tower, and electronics shelf. The optical bench uses a graphite cyanate (Gr-Cyn) face sheet and an isogrid core construction for maximum stiffness. It holds the beamsplitter, primary, secondary and fold mirrors, as well as the spacecraft star tracker and is kinematically supported with three titanium bipods with integrally machined flexures.

The relay tower contains the final four optics, the detectors, and the camera electronics. The tower mirror mounts are attached to 0.5-mm GrCyn face sheets using 25-mm-thick honeycomb composite panels. Its base is made of O.75-mm facesheets with 38-mm-thick honeycomb composite panels. Both sides of the tower are made from 1-mm-thick GrCyn sheets with angle stiffeners. The tower is kinematically mounted to the optical bench using GrCyn support tubes with a diameter of 13 mm, and a wall thickness of 1.4 mm.

The electronics shelf is mechanically separate from the other subassemblies, and is directly attached to the instrument adaptor ring. It is composed of 0.75-mm aluminum face sheets with 38-mm-thick aluminum honeycomb panels. The electronics are supported using titanium tubes with a 38-mm diameter and a 1.2mm wall thickness.

Preliminary NASTRAN models with more than 600 elements have demonstrated that the instruments is capable of surviving a 100 G static load and has its lowest mode at 40 Hz.

2.2.6 Software

The functions to be performed by the FAME instrument flight software will include:

- instrument timing and control,
- science data handling and on-board processing (target updates, rotation rate and attitude sensing),
- self-test functions, and
- ground support software for instrument integration and test.

The software will be written for three processors and can be uplinked from the ground. The R-6000 uses the VME architecture, which standardizes input-output (I/O) and control of peripheral hardware. The dominant computational load for the R-6000 is to sort 10 million-plus targets in the input catalog and extract the upcoming target list. The R-6000 easily executes the estimated number of flops. Its software will be written in object-oriented C programming language. High-speed data windowing and data handling of the science CCD outputs will be done by the 20 8051 microprocessors that are programmed during assembly. Finally, the rotation-rate will be computed by an 8OC86 microprocessor also programmed in assembly language. Table 2.2-3 lists the FAME instrument software modes and their operation sequence.

The functions to be performed by FAME ground support equipment (GSE) software include:

- simulation of spacecraft interface (sending commands and receiving instrument data),
- instrument monitoring (also used for mission operations),
- control of optical stimulus, and
- analysis of CCD calibration data.

2.2.7 Interfaces

The FAME design minimizes the number of interfaces between the spacecraft and the instrument. The instrument optical bench and electronics shelf are both kinematically attached to the spacecraft using three bipods that minimize thermo-mechanical distortion of the optical train.

The spacecraft star tracker is also kinematically mounted to the optical bench to maximize coalignment between the star tracker and the boresight of the instrument. The spacecraft star tracker is not electronically interfaced to the instrument.

The electronics interface between the FAME instrument and spacecraft is shown in Figure 2.1-7. The instrument computer transfers data to the spacecraft computer through a MIL-1553 bus and commands and housekeeping data through a RS-422 serial line. The spacecraft provides 28 Vdc, which the instrument converts and conditions. Coaxial cables transfer the oscillator and the flight system clock signal. The former is used to accurately time the star crossings and the latter is used to synchronize all on-board power supplies to reduce CCD read noise. A separate line will provide power for replacement heaters when the instrument is not functioning (i.e., during transfer and safing).

The Command Telemetry & Data-Handling (CT&DH) interface between the spacecraft and instrument is communicated through the MIL-1553 data bus and command serial line. Mission sequencing and control of attitude and rotation of the spacecraft will be controlled by the spacecraft computer. This operation is described in more detail in Sec. 2.1.5. The spacecraft will control the instrument through the operating modes shown in Table 2.2-4. The spacecraft will inform the instrument of its attitude and rate, which simplifies the star-acquisition process.

Table 2.2-4 FAME instrument software modes

OFF - Instrument computer is on but no operations are being executed.
SAFE - Replacement heaters are on.
STANDBY - Temperature controllers are operating by science sensors are turned off
ACQUIRE - Temperature controllers are operating.
- Grab attitude sensor information from spacecraft ACS (attitude and attitude rate).
- Sort star list for upcoming stars.
  - Acquire spin rate by centroiding.
  - Iterate to fine tune attitude information and narrow acquisition windows.

OBSERVE - Temperature controllers are operating.
  - Science data are taken and sorted.
  - Upcoming star list and positions of data windows are computed.
  - Rotation rate is computed and sent to readout electrons.
  - Attitude information is computed.
  - All instrument information is embedded into data packets, compressed, and sent to the spacecraft computer.

2.2.8 Integration and Test

The FAME instrument will be integrated and tested at JPL. Prior to the start of integration of any subsystem, it must pass a readiness and certification review. This review verifies that

- the subsystem has been fully tested and meets all requirements,
- the drawing/documentation package is complete to avoid a delay in troubleshooting during integration, and
- there is a complete set of handling and safety constraints.

Integration is divided into three areas: mechanical, electrical and software. The people responsible for these areas will be different than the cognizant subsystem engineers—although the subsystem engineers will be involved in all safety and troubleshooting discussions. This adds an element of independence to system testing. All problems/failures during integration and test will be documented. These will be resolved to the satisfaction of the subsystem engineers and the project manager before delivery of the instrument for integration with the spacecraft

The cognizant mechanical engineer is responsible for assembling all of the mechanical interfaces; handling, transportation, and fabrication of all thermal vacuum test fixtures; and for all facilities, including the Class-10,000 clean room used for integration. Early fit-checks will ensure a smooth mechanical integration.

The cognizant electrical engineer is responsible for connecting and verifying the simultaneous operation of the instrument's computer, telescope metrology electronics, signal chains, and camera heads. The spacecraft electrical interface will also be verified.

The cognizant software engineer is responsible for testing the operation of all software design modes and the robustness of the system to unintended commands. This engineer will be responsible for tracking the instrument's hours of operation to ensure that there is adequate "burn-in" of the electronics and that any "infant mortalities" will occur on the ground.

Environmental testing will include electro-magnetic interference and compatibility, vibration, acoustic, and thermal vacuum. The thermal vacuum test will verify the operation of the instrument over the full range of operating conditions, including the safe mode. An optical stimulus will enable a full end-to-end system test and science calibration. The stimulus collimates point sources and scans them across the instrument aperture. System tests will include image quality, time-delay integration, rotation rate sensing, stellar acquisition and data windowing, spectral calibration, and detector calibration over temperature.

2.3 FAME SPACECRAFT

The FAME Spacecraft bus is based on the Clementine S/C design. Whenever possible, existing hardware and software is used to reduce system development costs and increase confidence in cost estimates. The S/C will also leverage the technical and managerial expertise developed and maintained by the NRL Clementine project team.

The S/C is designed to fit into the 2.9-m Delta-Lite LV fairing as shown in Fig. 1-1. The mechanical interface to the LV uses the same hardware as the standard LV-provided 3712C Payload Attach Fitting. The LV-to-S/C separation hardware is provided by the LV vendor and the separation event is controlled the by LV. The S/C is stowed in the fairing in its flight configuration. No deployments are required, keeping the system simple and reliable.

All mechanical and electrical interfaces are kept simple to reduce time and cost of integration and test. All interfaces will be identified in appropriate and verifiable Interface Control Documents (ICD). The entire instrument assembly is attached to the bus at nine discrete points. All instrument-to-bus electrical connections are made at only two connector brackets. A simple internal truss structure carries all instrument loads. The S/C equipment is mounted on a single annular deck also attached to the internal truss. A fixed conical solar array attaches to the outer edge of the S/C equipment deck as well as to the LV interface ring. Figures 2.3-1 and 2.3-2 show the mechanical and electrical designs for the FAME S/C. Figure 2.3-1 also shows some commercial subsystems that will be integrated into the S/C.

2.3.1 Command Telemetry and Data Handling FAME Subsystem

The S/C controller is the same CT&DH Subsystem used on Clementine. It has seven modules: the Sensor Image Processor (SIP), the Data-Handling Unit (DHU), the Command (CMD) module, two Telemetry (TLM) modules, the Attitude Control System/Reaction Control System (ACS/RCS) interface module, and a power supply module. The modules are stretched standard electronic modules, Type E: (SEM-E) format, built with surface-mounted parts capable of withstanding a total dose of 20 krad.

The SIP, developed by Telenetics, Inc., is a commercially available, R3000-based, 32-bit reduced-instruction-set computing (RISC) processor. Low susceptibility to single-event upsets has been demonstrated with a total radiation dose of 20 krad. It provides instrument data processing, housekeeping and instrument data formatting, and control of the S/C command generation and telemetry collection. Image data are collected from the instrument across a MIL-STD 1553 interface between the instrument computer and the S/C controller and are buffered at peak aggregate rates of up to 50 kbits/sec.

The DHU controls the reading of the stored data, receives low-rate telemetry from the TLM module when in emergency backup mode, and performs wide-band framing for downlink at data rates of 1.024 Mbits/sec to 32 kbits/sec in 8 discrete steps.

The CMD module provides 48 high-level commands, 128 matrixed high-level commands, 32 low-level open collector commands, 8 differential commands, and 6 serial command channels. The TLM modules provide 48 bi-level telemetry channels, 48 active analog channels, 64 passive analog channels, 6 serial telemetry channels, and a backup low-rate telemetry downlink mode.

The ACS/RCS interface module controls 20 thrusters and two latch valves. Redundant oven-controlled crystal oscillators in the module control S/C time. These oscillators have drift rates of less than 50 μas/day. The power supply module receives +28 V from the Power Control Distribution Electronics (PCDE) and converts it to the +5 V, ±15 V, and wave-shaped +28 V that the S/C controller electronics require.

The solid-state Data Recorder (SSDR) from SEAKR engineering stores all the instrument image data. The SSDR is a flight-proven design with high reliability. Features include error detection and correction with active fault management, a built-in self test, and redundant control electronics in each unit. It has a data throughput greater than 20 Mbits/sec with a bit error rate less than one bit per 10 billion. The SSDR uses commercially available 16-Mbyte dynamic random access memory (DRAW, packaged as multichip modules. It is radiation tolerant to a 50-krad total dose. One unit will be flown for a total of 3.2 Gbytes of data-storage capacity.

2.3.2 Attitude Control Subsystem

The ACS attitude determination and control is used for FAME inertial pointing, rate control, and orbital maneuvers. Different levels of control are needed during the two phases of the mission: orbit transfer and science observation.

Table 2.3-2 ACS performance.

Attitude	Coarse (deg)	Fine (deg)
Knowledge	0.5	0.017
Control	0.3	0.010

Attitude Rate	Spin-Axis (mas/sec)	Transverse (mas/sec)
Knowledge	100	10
Control	5	5

During the orbit-transfer stage, coarse attitude sensing is provided by a Sun sensor and inertial reference unit (IRU). The Sun sensor has 4 Adcole SSA sensor heads each with a 64 x 64 deg FOV, and is capable of detecting the Sun an accuracy of 0.1 deg. The IRU is manufactured by Hughes Delco Electronics Corp. and contains 4 hemispherical resonating gyros capable of measuring the rate along each of three axes to better than 0.005 deg/hr (after calibration and filtering appropriate for this mission). A set of cold gas thrusters (see Section 2.3.1.7) is used for spin up/spin down as well as active nutation control during spinning operational modes. Coarse attitude sensing will enable the S/C to keep the Sun off the instrument at all times, including during S/C safes.

During science observation, precise attitude sensing is achieved by updating the IRU with a Ball CT-601 star tracker. On-orbit IRU biases and sensor alignment will be calculated from ACS and instrument data on the ground and uplinked to update the flight software. In flight, a simple sequential estimator (such as QUES) will be used for both coarse and precise attitude determination. Table 2.3-2 summarizes the ACS performance.

During the science observation phase it is desirable to minimize the number of thruster firings. This requirement translates into constraints on spacecraft inertias, CP and CM offset, and controller design. Constraining these clinical design parameters, as described in Section 2.1-3.3, will minimize the number of thruster firings required for attitude correction. No thruster firings will be required during a 90-deg scan.

2.3.3 Communications Subsystem

The radio frequency (RF) communications subsystem provides simultaneous commanding, telemetry, and tracking capabilities compatible with Deep Space Network (DSN) and NRL ground stations. This subsystem utilizes flight-proven, low-cost, high-reliability equipment. Two omnidirectional antennas assure that commands can be received when the S/C is at virtually any orientation. A single S-band solid-state transponder unit (based on the Clementine units developed by Loral Conic Corporation) provides the S/C uplink/downlink. A subcarrier oscillator and a convolutional encoder are included in the transponder. The transponder contains a 5-W solid-state transmitter and a phase-locked superheterodyne receiver. A diplexer, power divider, and switch are employed to minimize the effects of antenna pattern interference nulls. The receiver is powered at all times. S/C navigation requires ranging tones which are uplinked independently or during commanding. The tones are demodulated by the receiver and passed on to the transmitter for retransmission to Earth. Downlink data rates range from 1.024 Mbits/sec to 32 kbits/sec.

2.3.4 Structural Subsystem

The FAME structure must survive all mission loading events and protect the payload and other subsystems from excessive loads. In addition, the structure must provide adequate stiffness to avoid interaction between the structure and the ACS on orbit.

Twelve graphite composite tubes form a truss to which the instrument and all S/C components are attached (see Fig. 2.3-3). The struts are made from 8ply P75 graphite fibers in a polycyanate-ester resin. Aluminum end fittings bonded into the tubes use a scrim cloth separator to eliminate aluminum/composite contact. The end fittings attach to the spacecraft equipment deck. Instrument loads are passed directly through to the spacecraft truss structure by locating instrument attach points directly above the strut end fittings. The lower ends of the struts attach to an aluminum ring at 12 locations. This ring is attached to the upper half of the LV separation ring and to the lower portion of the solar array substrate. A lightweight one-piece graphite composite adapter mounts the Star 17 solid rocker motor (SRM).

The annular deck to which most of the S/C flight components are mounted, is an aluminum honeycomb sandwich construction. It attaches to the truss elements and the solar array substrate. The primary load path for the deck is the truss structure. Minimal loads are passed through the solar array. The array is sized to support its own weight (with required solar cells) and need not be present during integration of the structure. Brackets used to mount various components are made using inexpensive sheet metal. The single exception is the graphite battery structure flown on Clementine and used without modification by FAME.

2.3.5 Electrical Power Subsystem

The Electrical Power Subsystem (EPS) provides energy capture, storage, and distribution to all subsystems. A single lightweight, flight-proven, NiH2 common pressure vessel battery (15 A-Hr, 22 cells), developed by Johnson Controls, Inc., stores energy for use during eclipses and high-power usage activities. The battery is held by an ultra-lightweight graphite epoxy structure that doubles as the battery radiator.

The S/C solar array uses conventional silicon solar cells. The cells are mounted on the conical S/C body fixed graphite epoxy substrate structure. No deployments or mechanisms are required for solar array operation. The substrate structure is assembled from four identical sections, which were manufactured using the same tooling. This reduces manufacturing costs and facilitates installation; smaller substrates are easier to handle. During HEO and instrument operation, power output is a constant 350 W due to the axis-symmetric S/C geometry.

A single Power Control Distribution Electronics (PCDE) box distributes primary unregulated electrical power conditions primary electrical power provides circuit protection and monitors current, voltage, and selected temperatures. A separate JPL developed instrument power electronics box will condition and convert primary electrical power to meet instrument requirements. Excess energy production is limited by open circuiting individual solar array cell strings, no shunts are used.

2.3.6 Thermal Control Subsystem

The thermal control subsystem maintains all S/C component temperatures within design limits using materials and components with extensive flight heritage. All S/C electronics are mounted on the inboard surface of the annular S/C equipment deck. The deck also serves as a radiator with half of the external surface covered with Ag-teflon tape and the rest with MLI blankets. During peak power dissipation (~ 150 W), the deck will remain below 40° C. With all electronics off, 75 W of heater power are required to keep the deck above -10° C. The internal deck surface will be covered with MLI blankets to radiatively decouple it from the solar array structure and the solid rocket kick motor. The kick motor will be covered with high temperature beta cloth MLI. The battery has a separate 750-cm^2 radiator and 14-W heater to keep it below 20° C during discharging and above 0° C during charging.

While in the Sun, the solar array will be less than 40° C. In the FAME orbit, eclipse seasons occur twice a year with the longest eclipse 2.3 hours and the shortest 0.5 hours. During eclipses, the array cools to -150° C.

2.3.6 Propulsion Subsystem

The propulsion subsystem has two parts: STAR 17, to provide final orbit insertion (as discussed in Section 2.1.2), and a cold nitrogen reaction control systems (RCS) for attitude control during orbit insertion and data acquisition.

The nitrogen (N2) cold gas system was chosen for low cost, high reliability, and to eliminate propellant slosh. The N2 is stored in two 43-cm-diameter tanks at 25 Mpa. Four large thrusters spin and despin the S/C during solid rocket motor firing. Sixteen fine-control thrusters provide accurate pointing for astrometry. There is some redundancy in the thruster systems due to positioning thrusters without pure spin axis couples. The propellant delivery system is single string with latch valises both upstream and downstream of the pressure regulator to prevent gas leakage. The system contains high-and low-pressure transducers for system performance verification and in-flight telemetry.

2.3.8 Software

The flight software runs the spacecraft controller and includes algorithms for attitude determination and control, command and data handling, control of electrical power systems, and autonomous flight operations. FAME will reuse the Spacecraft Command Language (SCL) used on Clementine, giving the spacecraft an onboard scripting, as well as autonomous scheduling capability. SCL uses object-oriented programming techniques and includes a hyper-scripting language, a rule-based expert system, and classical programming language features. It allows both preemptive and multitasking modes, making it ideal for use in real-time applications. SCL automates many control tasks previously performed by ground personnel. The “C” programming language will be used for code development.

2.3.9 Integration and Test

Spacecraft integration and test flow is shown in Fig. 2.3-4. Prior to delivery, each hardware and software component will be subjected to box-level functional and environmental testing to ensure compliance with specifications. After delivery, it will again be functionally tested during integration with the flight vehicle. Functional and baseline performance testing will be performed both prior to and after system-level environmental tests, and when either the interface hardware or processing software is modified. Environmental testing at the next higher level commences after the successful subsystem integration. Operational software modes are tested to the maximum extent practical on the flight vehicle to verify the data flow and commands. These tests determine that each program branch, equation, and logic flow is executed correctly and that interfaces are implemented correctly. A software test bed, developed during the Clementine mission, is equipped with a high-fidelity dynamic simulation, including actual flight hardware and will support the verification of all attitude determination software and modes of operation. Launch support testing will be conducted to exercise each of the launch support configurations. The test scenarios will be performed per test procedures approved by the range prior to test initiation. All tests will be conducted using a set of PM-reviewed-and-approved test procedures. Satisfactory execution of all test procedures will provide the basis for verification of FAME and its component subsystems and will mark the completion of the test phase.

A hybrid development approach is chosen that incorporates “protoflight” development with the use of an engineering model (EM) spacecraft structure using mass simulators, flight mockups, and brassboard flight units. The EM serves as a pathfinder for the flight model testing. Testing that verifies compatibility of the spacecraft and FAME mission operations center's command and telemetry system will be conducted early in Phase III. Spacecraft and launch vehicle interface tests using LV-provided separation hardware will verify mechanical and electrical compatibility. RF compatibility tests will be conducted with the DSN and Pomonkey ground stations. An on-orbit simulation test, conducted during thermal-vacuum testing will demonstrate the readiness of the spacecraft and its flight operations team to conduct mission flight operations. The NRL spacecraft development team will maintain overall test and integration plans, test procedures, and a test log. A formal problem reporting system (including closeout data) for software and hardware anomalies will be utilized.

System-level testing of the flight article will be conducted to exercise each of the functional and performance requirements stated in the respective specifications. System testing is conducted to ensure that:

- detailed performance and design requirements, at the system level, have been satisfied,
- all system flight and ground interfaces have been exercised,
- system I/O performance satisfies the detailed requirements and has been thoroughly exercised,

- the integrated system can operate over the complete range of operating conditions (normal and abnormal), and
- all science calibration issues are understood and characterized.

Existing test and operations facilities at NRL and within industry previously used on Clementine will support FAME instrument, component, and spacecraft development, assembly, and test; environmental test; launch operations; and mission operations. No requirements for new or modified facilities have been identified and no new facilities are planned. The FAME spacecraft and its flight systems will be maintained under Class-100,000 contamination control from final assembly to mating with the payload. The integrated payload and spacecraft will be maintained under Class-10,000 contamination control through delivery to the launch vehicle and subsequent launch. To assure optical cleanliness, a localized clean tent capable of maintaining the optics to Class-1,000 contamination control will be used during any period that the optical sensors are exposed. Additionally, the S/C will be equipped with a localized nitrogen purge in the area of payload optical bench during all integration and test activities and at the launch site. There are no requirements on magnetic field during integration or testing. Personnel handling electronics will be required to wear grounding straps to eliminate electrostatic discharge (ESD).

2.4 GROUND SYSTEM AND OPERATIONS

For the FAME mission, Ground System and Operations are broken into three functional entities: Networks, Mission Operations, and Data Handling. NASA will perform all of these functions.

2.4.1 Networks

The DSN will be used for all phases of the mission. Near perigee and apogee, the link margins support the use of both the 26-m and 34-m networks respectively. Standard DSN capabilities will meet all mission requirements. The FAME mission will require 4 hours per day of DSN support, including 2 hours of Mode A and 2 operations of Mode B support to lessen the impact on DSN. In Mode A, each DSN site will collect telemetry, ranging, and range-rate data. In Mode B, only telemetry and range-rate data will be collected (no range data). NRL will examine the use of its Pomonkey Telemetry and Command site in the event that resource conflicts prohibit DSN support at the required levels. Range and range-rate data will be supplied to the Mission Operations Center (MOC) for orbit determination. More details on the S/C communications parameters can be found in Section 2.3.1.3.

The S/C transponder supports 8 selectable bit rates to maximize downlink data rates while required DSN antenna size and contact times. The transponder modulates the carrier with one channel of interleaved science and state of health telemetry data for all downlink bit rates. However during tracking, the carrier is used as a ranging channel and telemetry data are modulated onto the 1.7-1&U subcarrier. In this mode, the downlink bit rate is limited to a maximum of 128 Kbits/sec.

Two compatibility tests will ensure RF compatibility between the -9C and DSN. Prior to final acceptance testing at the manufacturer, the FAME transponder will be transported to Compatibility Test Area-21 (CI7A-2 1) at JPL for initial compatibility test. After the RF subsystem is fully integrated to the S/C bus, the CTA-21 test van will be transported to the launch site for the second compatibility test. These tests will be used to optimize the DSN configuration.

2.4.2 Mission Operations

Goddard will provide a Flight Operations Team (FOT) to monitor S/C health and safety around the clock. The FOT will also provide standard activity and event planning and scheduling. FAME should require minimal operations after the first 30 days; the preloaded observation program for the entire mission runs autonomously.

The FAME mission will be supported by the MIDEX common MOC for nominal operations and anomaly resolution. The MOC will provide all standard functions for S/C operations and data handling, including planning and scheduling S/C operations, S/C control, S/C performance analysis, and real-time contacts. NRL and JPL will supplement mission operations resources as required. The MOC will be linked to DSN sites via the NASA Communications (NASCOM) system, which will provide pathways for telemetry, command, tracking, monitoring voice, and file transfers.

The FOT will be augmented by a small group of subsystem engineers located at the MOC for launch and special operations. It is anticipated that the size of this group of engineers will decrease as the FOT gains proficiency in

FAME S/C operations. By Launch +31 days, it is anticipated that the mission operations team will consist primarily of the FOT. Throughout the mission, an S/C engineer and an instrument engineer will be on call 24 hours per day for anomaly resolution. If an anomaly occurs, the S/C engineer will ensure that the S/C is put into, or has gone into, a safe mode, then contacts the appropriate S/C or instrument subsystem specialist(s) to troubleshoot the anomaly and recommend further actions. During critical mission phases and maneuvers (i.e. launch, kick motor burns), a team of NRL subsystem specialists will be located at the MOC for immediate anomaly resolution.

NRL and JPL will provide a complete *Orbital Operations Handbook* to document all S/C and instrument operational modes and constraints. These will also be summarized in a rules and constraints document. All interfaces will also be documented in the ICD.

2.4.3 Data Handing

The MOC will receive and record the near-real-time telemetry stream. The MOC will remove communications artifacts from the raw data and then sort, order, and assemble it into data sets, so that it can be delivered to the Science Operations Facility (SOF) via the Internet. The S/C and instruments' state-of-health data will be displayed in real-time on multiple terminals at MOC. S/C commands will originate from the MOC in real-time mode and will be sent via NASCOM links to the ground network for uplinking in real-time to the S/C.

3.0 DATA REDUCTION AND ANALYSIS PLAN

3.1 CATALOG GENERARATION

Data reduction leading to a catalog of positions, proper motions, and Parallaxes for the 10 million program stars can be broken into a number of discreet steps: first-look tasks, build up of angles between stars, spectral filling to determine rotation axis attitude, great circle reductions, sphere reconstruction, astrometric parameter determination, final spectral determination, and data distribution. The approach is similar to Hipparcos data reduction.

3.1.1 First-Look Tasks

Data being gathered from the FAME satellite must be checked immediately after downlink to ensure that the hardware and software are working correctly. A stars timing and image quality pattern will be checked against the input catalog. A subset of the stars will be centroided and spectra fit so that a "first-look" solution to the attitude and basic angle can be made. Any anomalies discovered in the data will trigger anomaly recovery activity, involving the mission and science operations teams.

3.1.2 Build-Up of Angles

As the FAME satellite slowly rotates, a swath of sky along a great circle is scanned by two FOVs. Timing of the "transits" of the images multiplied by the rotation rate produces an angular separation between stars along the scan direction. A value for the rotation rate can be determined using all stars crossing the rotation-rate CCD. Since rotation-rate knowledge is lost during ACS thruster firings, it is necessary to overlap consecutive scans by at least 50% and to ensure that thruster firings do not occur at the same moment in consecutive scans. If both rotation-rate CCDs fail, the angular velocity can be determined iteratively—with some loss of accuracy—from the input catalog positions. In this scenario, a subset of stars will be scanned on three consecutive rotations of the satellite. Star images that are a superposition of two (or more) individual stars will be flagged as multiple and will not be used to calculate origins in the great circle reductions or the sphere reconstruction step.

3.1.3 Spectral Fitting to Determine Rotation Axis Attitude

It is important to determine the attitude of the satellite rotation axis to better than 100 mas to minimize errors due to projection effects in the FOV. Attitude knowledge of this precision cannot be obtained from the star tracker; hence, observational data must be used. The cross-scan position on the CCD where a star crosses could be used; however, the light from the stars are dispersed in the cross-scan direction. This means that cross-scan attitude determination can only be obtained from stars whose spectra are known *a priori*. Data from the Hipparcos and

Tycho missions will be used for this task. Each star will yield a value for the cross-scan direction accurate to 400 mas. Using all stars between ACS jet firings will yield a cross-scan direction accurate to 20 mas.

3.1.4 Great Circle Reductions

The angular separations of stars determined during each great circle scan, and the attitude knowledge, will be used to calculate 1-dimensional positions, called *abscissae*, along each great circle. Strong closure conditions exist for each great aide scan, allowing the transformation between the sky and the focal-plane coordinates to be calculated. This calculation yields values for the basic angle, scale, and field rotation. Accurate a priori positions for a subset of stars in each great circle is required to estimate its origin. However, each great circle will still contain a small, arbitrary rotation. This rotation is solved for in the sphere reconstruction stage.

3.1.5 Sphere Reconstruction

Each great circle scan defines an independent coordinate system. In the sphere reconstruction step, these systems are all brought together to form a single, global system. This is achieved by solving for the great circle origins and the astrometric parameters of a subset of stars using the abscissae from the great circle reductions. It is important to use only stars whose motions are well behaved; stars suspected of multiplicity are avoided. It is envisioned that a subset of Hipparcos stars will be utilized for this purpose.

3.1.6 Astrometric Parameter

Calculating the five astrometric parameters (position, proper motion and parallax) is achieved by combining data from the sphere reconstructions to build up a system of equations for each star. Statistical tests for spurious motion, which could indicate multiplicity, are also run. Those stars suspected of multiplicity will be noted and treated separately.

3.1.7 Iterations

Data reduction for FAME must be an iterative process. The cross-scan determination, great circle reductions, sphere reconstruction, and determination of astrometric parameters are all affected by the accuracies of the input catalog. After completing the reduction process once, the new astrometric data can be substituted into the cross-scan attitude-determination process. Multiple stars not formerly recognized as such will be dropped from the sphere reconstruction step. It is believed that two or three iterations will be needed before final solutions to positions are obtained.

3.1.8 Final Spectral Type Determination

Using the final astrometric parameters, spectral information for individual observations of each star is analyzed, producing an estimate of each star's spectral type.

3.1.9 Schedule and Data Distribution

It is envisioned that the final catalog will be available to the public about 1.5 years after the mission is completed. However, since completion of data reduction prior to the first iteration will realize an order-of-magnitude higher-accuracy than existing catalogs, it will be made available to the science team as soon as it is completed. Distribution of a catalog of this size (on the order of 5 Gbytes) can be done using a variety of currently available media.

4.0 MANAGEMENT PLAN

4.1 MANAGEMENT ORGAN1ZATION

We propose an experienced team to meet the challenge of providing a scientifically and technologically advanced mission to NASA at a minimum cost. Each team member possesses specialized and unique expertise that is needed to build FAME. The Principal Investigator (PI) mode is proposed for FAME because, if selected, the Department of Defense (DoD) will provide the FAME spacecraft at no cost to NASA. The Principal Investigator, who is also the Scientific Director of USNO, will use JPL as the project management organization. The organization of the institutions and people that will be committed to the FAME Project is discussed in the following sections, and is depicted in Figure 4. 1-1.

4.1.1 The United States Naval Observatory

Founded in 1830, the USNO performs a number of essential scientific roles for the United States, the Navy, and the DoD. Its mission includes measuring the Earth's rotation, determining the positions and motions of the Earth, Sun, Moon, planets, stars, and other celestial objects, and assembling them into star catalogs to establish reference frames. The USNO employs a number of facilities in both hemispheres to carry out its astrometric observations. These include transit circles, astrometric telescopes, the Mark III stellar interferometer on Mt. Wilson in California, and the nearly completed Navy Prototype Optical Interferometer in Flagstaff, Arizona.

Dr. Kenneth Johnston, USNO Scientific Director, serves as PI for the FAME mission. As PI, he will be accountable to NASA/GSFC and the Navy for all aspects of the mission, including the on-time and on-budget delivery of the instrument payload, spacecraft, ground data-analysis system, and archival data products. He provides overall guidance for scientific aspects of the mission. He will organize and lead the science team and the scientific investigation, including the timely reduction and dissemination of data to the science community. The USNO will provide the Science Operations Center and science support during the mission operation phase.

4.1.2 The Jet Propulsion Laboratory

JPL is a NASA facility operated for NASA by the California Institute of Technology. JPL is a world leader in the design and development of technologically advanced scientific missions and instruments, including the first satellite flown by the United States (Explorer- 1), the first spacecraft to explore the outer planets of the Solar System (Voyager), and most recently, the Wide-Field and Planetary Camera-2 (WFPC-2), which is now returning optically corrected images from the Hubble Space Telescope (HST). JPL is the lead center within NASA for optical interferometry, and has built and operated ground-based interferometers specifically designed for precision astrometry, including the nearly completed Palomar Testbed Interferometer. JPL is uniquely qualified to provide the innovative instrument payload for the FAME mission.

JPL will provide the Project Manager for FAME development, who will be responsible to the Principal Investigator for ensuring that:

- all elements of the FAME mission are developed to a consistent set of requirements that support the agreed-upon science requirements, over-all mission budget, and schedule;
- the instrument Payload is delivered on budget and on schedule; and
- the PI is provided with timely and up-to-date reports of overall project status.

4.1.3 The Naval Research Laboratory

NRL is the Navy's corporate research laboratory, with an extensive history of spacecraft development, including over 80 individual satellites and 32 launches. NRL maintains in-house facilities and staff to support all phases of spacecraft development, integration and test, and operations. Most recently, NRL was the executing organization for the highly successful Clementine satellite, which pioneered a new paradigm of fast-paced, low-cost mission development.

NRL will provide the FAME spacecraft using an experienced team of individuals fresh from the Clementine program. NRL will perform the system-level integration and test, integration support to the launch vehicle, and will lead the initial in-orbit checkout of the satellite. NRL will provide operations handbooks and documentation to enable the GSFC Flight Operation Team to take over operation of FAME satellite 30 days after launch. NRL will provide the Deputy Project Manager, who will work closely with the Principal Investigator and the JPL Project Manager.

4.2 MANAGEMENT PHELOSOPHY AND APPROACH

The FAME Project will operate in a mode that stresses the importance of containing costs. We will set realistic requirements that satisfy the baseline science investigation and that we are confident of meeting with low cost or schedule risk. The FAME Project will employ a simple, streamlined set of practices and processes to ensure that project risk is understood and controlled. Emphasis is placed on establishing clear lines of accountability for products. A person, not an organization, will be responsible for each project element.

The partnering institutions will stress a “badgeless team” approach, and will maintain a systems engineering focus throughout definition, development, and test activities. Complete, accurate, and timely programmatic forecasts and reports will assure project-wide visibility of all aspects of the development. Risk-mitigation plans will be developed early, and descope paths will be continually maintained to preserve cost and schedule integrity. Frequent and rapid communication (emphasizing use of the Internet) will ensure tight coordination of requirements and interfaces.

4.2.1 Decision-Making Process

The FAME Project will implement a set of management processes designed to provide dearly defined interfaces and uniquely identifiable and manageable communication channels for decision making. Regularly scheduled reviews, including a standing review board of technical and management advisors, are designed to promote consensus decisions among USNO, JPL, NRL, and GSFC team members. Each of the major deliverable element managers—the Space Segment Manager (space-craft), Payload Manager (instrument payload), and Principal Investigator (data analysis segment) —are empowered to exercise decision authority over their respective elements in order to meet the agreed-upon technical, cost, and schedule requirements. The JPL Project Manager, assisted by the NRL Deputy Project Manager (DPM), will have responsibility and authority to assure that all major deliverable elements are built to consistent requirements and interface agreements, and that they will function together as a system to meet the Project Level 1 requirements.

Descope decisions will follow agreed-upon processes, with identifiable decision points and descope criteria, developed in advance. We acknowledge that certain conflicts may develop that will require special attention. In this case, the Project Manager will submit a set of decision options and a recommendation to the PI. The PI will make a decision after consulting with the GSFC MIDEX office.

4.2.2 Management Oversight Board

An oversight board has been established to assure alignment among institutional members of the FAME team, and to avoid serious problems. The board may be convened on an ad-hoc basis by any of the Project participants to resolve top-level issues that have not been resolved by conventional project management mechanisms.

4.2.3 Technical Coordination

The FAME Project will stress early documentation of requirements and interface agreements as a part of the baseline design for configuration control purposes. We will minimize the engineering change proposal process by controlling subsystems and major deliverable elements at interface levels rather than by detailed specification.

4.2.4 Meetings and Reviews

Weekly teleconferences will be held between the JPL Project Manager, the NRL Space Segment Manager (who is also the DPM), the JPL Payload Manager, and the PI. Technical interchange meetings will be convened as required to assure smooth interaction among the project team. Informal monthly management meetings (MMM) will be held, alternating between the East and West Coasts. The MMM will have a standing review board of advisors to provide sage advice and continuity of the review process.

Peer reviews will be held to provide important stimulation and consultation at the subsystem level. These peer reviews will precede to the formal reviews discussed in Section 2.1.7.

4.2.5 Product Assurance

We will conduct a cost-effective tailored mission assurance program, in accordance with JPL and NRL internal mission assurance standards, that meets the intent of the MIDEX Assurance Requirements, GSFC-410-MIDEX-002. The mission assurance program will incorporate quality assurance activities, reviews and system safety, and will be implemented concurrently with the design activities. It will emphasize verification by test and will include a failure reporting system that provides management oversight. Specific upgrades to enhance reliability of the flight hardware will be used as appropriate. Past project “lessons learned” will be incorporated to assure that the flight hardware with inheritance from or derivatives of other designs do not contain weaknesses which could lead to flight hardware failure.

4.3 SCHEDULE

We propose an aggressive schedule for FAME, shown in Fig. 4.1-2. Phase 1 will be eight months in duration. During Phase 2 the instrument payload and spacecraft will enter detailed design; long lead procurements will be placed. One month into Phase 3 we will convene the instrument CDR and freeze its requirements and interfaces with the spacecraft. Three months later the mission CDR will be convened, where the entire mission configuration will be frozen.

Phase 4 will 1ast for four years, including a 2.5 year data acquisition period, during which concurrent data analysis will proceed. One year after completion of the flight portion of the investigation, we will release the final archival catalog to the science community at large. Science analysis will continue for an additional six months.

4.4 DETAILED MANAGEMENT PLAN

A detailed management plan will be provided as a part of the FAME Step 2 proposal. This plan will include information in the following areas:

- Teaming agreements and funding mechanisms
- Organization and accountability
- Key project and subsystem personnel
- Management and technical coordination
- Margin and reserve policy
- Risk and descope process
- Task control and administration
- Formal reviews and reporting
- Configuration management
- Documentation approach
- Mission assurance
- Performance verification process
- Contract management
- Project schedule
- Operations and data management
- Facilities

5.0 COST PLAN

The FAME mission was conceived to minimize both the total cost and the cost to NASA. In this section, we describe our cost-saving strategies; the basis of our "bottom-up” or “grass-roots” cost estimates, highlighting the inheritance used in the FAME systems; and the independent validation of the grass-roots estimate using a model based on JPL’s and NRL’s extensive experience in spacecraft and instrument systems.

5.1 PARTNERSHIP, DESIGN AND IMPLEMENTATION STRATEGIES

Developing a mission with the revolutionary capabilities of FAME at such an affordable price to NASA involves several different strategies. These strategies focus on a low total mission cost and reducing the cost to NASA, as described below.

5. 1. I Partnership

The JPL, USNO, and NRL partnership brings the complementary scientific and engineering capabilities of our organizations to the implementation of a space project that will make a major contribution to the missions of both NASA and the Navy. Reflecting its importance to the Navy, the DoD will be contributing the entire cost of the spacecraft, providing a portion of the MO&DA cost, and archiving the data.

5.1.2 Design and Implementation

We have developed a design and implementation approach which yields a total cost of less than $70M for Phases 1, 2, and 3. This includes both the NASA and Navy contributions. A number of key strategies have made this low cost possible.

5.1.2.1 Experience

The FAME mission draws heavily on prior astrometric programs in the U.S. and Europe. It draws on the European Hipparcos mission design and observational strategy. It makes effective use of existing U.S. technology in optics, detectors, and signal processing to radically improve performance and dramatically reduce the size and cost of the flight system and ground operations. FAME also draws upon the JPL's experience in design and technology development for space astrometric missions and USNO and JPL experience operating the ground-based optical interferometers.

5.1.2.2 Flight System Design

The flight system is a simple, yet elegant design with no moving parts that executes a single straightforward data acquisition sequence. A very compact lightweight telescope—a 36 in focal length in a 1.3 in cube—allows the use of a small Delta-Lite launch vehicle (Hipparcos used an Ariane IV). Both the spacecraft and the instrument take advantage of cost-saving technologies that have been recently space qualified.

Some examples are:

- spacecraft technologies proven on the Clernentine mission, including composite bus structures, data storage subsystems, and power subsystems.
- large area back-side illuminated CCDs made possible by advances in silicon foundry technology. These collected two orders of magnitude more photons than the image dissector tubes used by Hipparcos and are less expensive, and
- a separate CCD-based star tracker for spacecraft attitude referencing which eliminates the need for a large ground operations team to determine spacecraft attitude from the science data (the approach used by Hipparcos).

5.1.2.3 ***Mission Design***

The mission design further simplifies the flight system and its operation. For example:

- the flight system is inserted into an orbit that requires only a cold gas attitude control system and involves no complex maintenance and trim maneuvers,
- the orbit permits communication and tracking with robust margins without the use of a high gain antenna and specialized pointing sequences and
- both the S/C and instrument are designed for autonomous operations.

5.1.2.4 Margins in Capability

Experience dictates that margins in capability are the key to low cost and low risk. The FAME mission has been designed with substantial margins for all key subsystems. Some examples are:

- the design has large mass (51%) and power margins (31 %),
- the computers for both spacecraft and instrument have large margins in computing power and accommodate a powerful operating system, and
- the data recorder is large enough to preclude the need for costly and expensive systems for managing data acquisition and communications sequences.

5.2 HERITAGE AND BASIS OF ESTIMATE

The design and implementation approach adopted for FAME depends on extensive use of flight proven hardware and the application of experience where new designs are needed. Tables 5-1 and 5-2 show the heritage for each of the major subsystem elements and detail the basis of costs. In general, these costs were developed by the JPL, NRL, and USNO engineers responsible for the work and quotes from subcontractor. They have been critically scrutinized by project management for completeness and to ensure the most cost effective approaches have been adopted.

5.3 COST ESTIMATES

5.3.1 Bottom-Up Cost Estimate

Figure 5.3-1 shows the FAME Work Breakdown Structure (WBS). A summary of estimated costs for Phases 1 through 3 and for Phase 4 of the FAME mission by WBS element appears in Table 5-3. The shaded items are contributed by the DoD at no cost to NASA. The total cost through Phase 3 is $69.5M, and the cost for MO&DA is $12M in FY94 dollars. **The cost to NASA through Phase 3 is $43M and the cost for MO&DA is $9.0M in FY94 dollars.**

A more detailed assessment of costs by Phase for the immediate definition option appears by WBS element in Table 5-3. The extended definition option is also shown in the table. We anticipate no additional costs in the extended definition mission option measured in FY94 dollars. However, when accounted for in real-year dollars, the extended definition option is slightly more expensive as a result of the effects of inflation.

5.3.2 Parametric Cost Verification

To validate the spacecraft cost, NRL used a version of GE-Price, a mass-based parametric cost estimating model used for predicting development costs, production costs, and schedules, to develop an independent verification of the spacecraft cost estimate. Consistent assumptions were made in setting up the GE-Price model and the bottom-up cost estimate.

As an independent validation of the NRL costs, JPL performed parametric estimates of the spacecraft bus using the JPL Project Cost Model. The JPL Project Cost Model is an in-house model which has been used and updated for the last 27 years to support project commitment estimates. It has been successfully used to provide commitment estimates for successful low-cost missions such as the Solar Mesospheric Explorer.

The estimates provided by NRL and those independently generated by experienced JPL estimators using the JPL Project Model for the spacecraft bus were within 5% of each other. A cost review of FAME was held by JPL senior management resulting in an endorsement of this

5.3.3 Reserve Policy

For the NASA portion of the budget we have included a 15% reserve on all WBS items through Phase 3, with the exception of the instrument payload, where we have included a 30% reserve. This is reasonable given the inherently higher degree of technology associated with the instrument payload. All Phase 4 WBS items have a 5% reserve added.

The DoD takes full responsibility for delivering the spacecraft at no cost to NASA, and will maintain its own reserve, not included in Table 5-3.

5.3.4 Alternate Investigation Cost

Should FAME be selected as an alternate investigation, we would require $250K per year in FY94 dollars for one or two years to conduce preparatory definition studies and to maintain a nucleus of the investigation team.